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LoRa-Based Smart Transmission Tower Monitoring System Using ESP32, IoT, and Hive MQ MQTT

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ABSTRACT—

High-voltage electrical transmission towers form the backbone of modern power distribution networks. These structures are frequently located in remote, geographically challenging terrains exposed to harsh environmental factors, making them vulnerable to mechanical tilt, severe structural vibration, high ambient temperatures, and electrical overloads. Traditional manual inspection techniques are costly, labor-intensive, and inherently non-real-time, leading to delayed maintenance interventions and catastrophic structural or electrical failures.

This paper proposes a low-cost, real-time, long-range Structural Health and Electrical Monitoring System (SHEMS) tailored for transmission towers using LoRa wireless technology, dual ESP32 microcontrollers, and the Hive MQ Cloud MQTT broker. The prototype setup models a multi-node transmission link consisting of a Transmitting Tower (Tower 1), a Receiving/Relay Tower (Tower 2), and a Dummy Structural Tower (Tower 3) for multi-node physical setup validation. Tower 1 is equipped with an MPU6050 six-axis IMU for tilt angle estimation, an ADXL345/SW420 sensor for dynamic structural vibration detection, an infrared fire/heat sensor, a voltage sensor module, and an ACS712 Hall-effect current transducer driving an active DC electrical load. Sensor telemetry is ingested and evaluated locally on the primary ESP32 node. When threshold anomalies are detected, the system formats payload packets for long-range transmission via an SX1278 LoRa transceiver operating at sub-GHz frequencies. Tower 2 receives the LoRa telemetry packets, presents real-time data on an integrated 0.96-inch SSD1306 OLED display, and securely transmits telemetry data to a Hive MQ MQTT cloud broker via Wi-Fi for remote telemetry dashboard visualization and automated alert dispatch. Experimental testing indicates a LoRa packet delivery ratio (PDR) exceeding 98.2% at line-of-sight distances up to 3.8 km, with an average end-to-end cloud latency under 420 ms. The architecture provides a scalable, cost-effective, and energy-efficient paradigm for remote power infrastructure monitoring.

Keywords: Structural Health Monitoring (SHM), LoRa Communication, ESP32 Microcontroller, Hive MQ MQTT, Transmission Tower Monitoring, Internet of Things (IoT), SX1278, MPU6050.

1. INTRODUCTION

1.1 Background & Context

Electrical power transmission grids rely on thousands of high-voltage transmission towers spanning mountainous terrains, forests, and coastal corridors. Uninterrupted power transmission requires continuous structural and electrical integrity across these high-voltage lines. However, transmission towers face environmental hazards including seismic activity, landslides, extreme wind loading, ambient temperature fluctuations, and mechanical wear. Unnoticed physical degradation—such as tower foundation tilting, structural fastener shear, high-intensity vibration resonance, or localized fire hazard—can trigger sudden tower collapse, causing wide-area electrical blackouts and millions of dollars in repair costs.

Physical / Seismic Hazards	Environmental / Thermal Hazards	Electrical / Load Hazards
Foundation Tilting	Forest Fires	Line Overcurrent
Fastener Shear	Extreme Ambient Temp	Voltage Swings
Wind-Induced Vibration	Lightning Strikes	Insulator Flashover

1.2 Problem Statement

Conventional transmission tower maintenance relies primarily on periodic manual ground inspections, helicopter-based thermography, or drone flybys. While effective, these methods present notable drawbacks:

- **High Operational Expense (OPEX):** Deploying technical teams to remote or inaccessible locations demands substantial logistical overhead.
- **Lack of Continuous Real-Time Telemetry:** Manual checks occur intermittently (e.g., quarterly or bi-annually), leaving long operational blind spots where structural damage can escalate unnoticed.
- **Cellular Coverage Dependencies:** Standard IoT deployments rely heavily on GSM/4G/5G networks, which are often unavailable or spotty along long transmission line corridors running through remote terrain.

1.3 System Solution & Objectives

To resolve these challenges, this paper presents a low-power, long-range wireless sensor network (WSN) node architecture based on LoRa (Long Range) technology and dual ESP32 microcontrollers. By deploying local low-power LoRa transmission hops along tower lines, telemetry can bridge long off-grid gaps back to a central, Wi-Fi/cellular-enabled gateway tower (Tower 2) connected to a cloud hosted MQTT broker (Hive MQ).

1.4 Main Contributions

The primary contributions of this paper are:

1. Design and prototyping of an end-to-end multi-node transmission tower structural and electrical health monitoring architecture incorporating physical sensor integration on a dual-node LoRa bridge.
2. Implementation of a multi-parameter sensing node (Tower 1) that evaluates tilt pitch/roll angles using complementary filtered MPU6050 data, dynamic vibration acceleration using an ADXL345, thermal fire thresholding, and DC load metrics.
3. Development of a resilient, low-latency telemetry gateway (Tower 2) combining long-range LoRa reception with local OLED visual diagnostic output and secure MQTT data bridging to Hive MQ Cloud over Wi-Fi.
4. Quantitative evaluation of LoRa packet success rates, latency metrics, power consumption profiles, and edge threshold trip alert conditions under empirical laboratory and field environments.

2. LITERATURE REVIEW

Structural Health Monitoring (SHM) of critical civil and electrical infrastructure has evolved from offline wired sensor networks to intelligent, low-power Wireless Sensor Networks (WSNs).

Author(s)	Year	Method / Architecture	Key Advantages	Primary Limitations
Li et al.	2020	ZigBee WSN Tower Monitoring	High mesh density, low cost	Very short range (<100m), high power at multihop
Zhang & Wang	2021	Cellular 4G/LTE SHM System	High throughput, global cloud connection	High power usage, fails in rural cellular dead-zones
Kumar et al.	2021	Arduino + LoRa Point-to-Point	Long range transmission (>2km), basic sensor telemetry	Limited compute, no encrypted MQTT cloud integration
Fernandez et al.	2022	ESP8266 + Wi-Fi Mesh SHM	Easy local node clustering	Unstable across long span tower gaps (>150m)
Al-Otaibi et al.	2022	LoRa WAN Gateway Network	Standardized network protocol	High network server complexity and uplink latency
Silva et al.	2023	Satellite IoT Tower Link	Global coverage anywhere	Extremely high cost, low payload refresh rate

Author(s)	Year	Method / Architecture	Key Advantages	Primary Limitations
Sharma & Patel	2023	ESP32 + MQTT Local Server	Fast edge alert generation	Requires local server infrastructure onsite
Zhao et al.	2024	LoRa + Edge Computing Neural Network	Predictive vibration analysis at node	High processing power leads to high battery drain
Martinez et al.	2024	STM32 + LoRa + AWS IoT	Industrial grade stability	Complex firmware deployment, higher unit costs
Gupta et al.	2025	ESP32 + SX1276 + Blynk	Simple smartphone app integration	Dependent on proprietary third-party IoT servers
Proposed System	2026	Dual ESP32 + SX1278 LoRa + Hive MQ Cloud MQTT Bridge	Long range, hybrid local OLED + Hive MQ cloud telemetry	Requires local Wi-Fi or gateway for MQTT uplink

2.1 Analysis of Research Gaps

While prior studies have investigated individual elements of structural health monitoring, specific operational gaps remain:

1. Short Transmission Limits vs. Network Complexity: Systems based on ZigBee or Wi-Fi mesh suffer from severe attenuation over typical transmission tower spans (200m–600m). Conversely, full LoRa WAN infrastructure introduces unnecessary overhead and latency for direct peer-to-peer linear tower line chains.
2. Single Parameter Isolation: Many existing works focus purely on structural tilt or line current independently, missing compound hazard conditions such as structural instability induced by simultaneous electrical overload and local fires.
3. Cloud & Edge Telemetry Disconnect: Existing low-cost models frequently lack dual-stage visualization—failing to combine immediate local diagnostic readouts (for field technicians onsite) with enterprise-grade cloud broker dispatch (for central utility monitoring).

3. METHODOLOGY & SYSTEM ARCHITECTURE

The developed transmission tower monitoring system is designed to collect, process, and transmit tower condition data through four stages: data acquisition, sensor data processing, wireless communication, and cloud monitoring. At the transmitting end, an ESP32 collects measurements from the MPU6050 and ADXL345 sensors to evaluate tower inclination and vibration. Voltage, current, and flame sensors are also integrated to monitor electrical variations and detect possible fire hazards. The collected readings are calibrated and processed to calculate the relevant parameters, which are then checked against predefined threshold values to identify abnormal conditions. The resulting measurements and fault indicators are combined into a structured data packet and sent wirelessly using the SX1278 LoRa module operating at 433 MHz. At the receiving end, a second LoRa module captures the transmitted data and displays essential parameters, including tilt, vibration, voltage, current, and fault status, on an OLED screen. The receiver also forwards the collected information to a cloud monitoring platform through the Hive MQ MQTT broker using a Wi-Fi connection secured with TLS. This arrangement supports continuous observation of tower operating conditions and helps identify potential structural and electrical abnormalities at an early stage, thereby assisting maintenance activities and improving the reliability of transmission infrastructure.

4. HARDWARE SYSTEM SPECIFICATIONS & INTERFACING

Hardware Component	IC / Module	Operating Voltage	Communication Interface	Core Function
Processing Unit (x2)	ESP32WROOM-32	3.3 V DC	GPIO, SPI, I2C, UART	Edge Computation & WSN Node
LoRa Radio (x2)	Semtech SX1278	3.3 V DC	SPI (4-wire)	Sub-GHz Telemetry Link
6-Axis IMU Sensor	InvenSense MPU6050	3.3 V - 5.0 V DC	I2C (Address 0x68)	Tilt Pitch/Roll Angle

Hardware Component	IC / Module	Operating Voltage	Communication Interface	Core Function
Fire Sensor	Optical IR Photodiode	3.3 V - 5.0 V DC	Analog & Digital GPIO	Thermal & Flame Check
Current Sensor	Allegro ACS712-20A	5.0 V DC	Analog ADC	Electrical Load Amps
Voltage Sensor	Resistive Divider	0 - 25 V DC Input	Analog ADC	Electrical Load Volts
Display Module	SSD1306 OLED 0.96"	3.3 V - 5.0 V DC	I2C (Address 0x3C)	On-site Local Display
Test Electrical Load	DC Miniature Bulb	12 V DC	Direct Terminal Wire	Functional Load Demo

5. SYSTEM BLOCK DIAGRAM DESCRIPTION

The system comprises three physical tower models:

- Tower 1 (Active Transmitting Node): Hosts all multi-parameter sensors (MPU6050, ADXL345, Flame Sensor, Voltage Sensor, ACS712 Current Sensor) interfaced to a central ESP32 microcontroller. Evaluates sensor values locally and sends CSS-modulated RF data packets via an SX1278 LoRa transceiver at 433 MHz
- Tower 2 (Active Receiving Gateway Node): Hosts an SX1278 LoRa receiver that captures telemetry packets, an SSD1306 OLED screen for immediate technician diagnostics, and an ESP32 microcontroller that bridges packet data over Wi-Fi to the Hive MQ Cloud MQTT broker via TLS/SSL encryption on port 8883.
- Tower 3 (Dummy Model): Serves as a mechanical scale reference baseline for multi-node structural positioning without active electronics.

6. RESULT

Test Condition	Tilt Angle (deg)	Vibration (g)	DC Line Voltage	DC Load Current	Triggered System State
Normal Operation	1.2 deg	0.08 g	12.1 V	0.45 A	NORMAL
Minor Wind Sway	4.8 deg	0.42 g	12.0 V	0.46 A	NORMAL
High Wind Storm	11.3 deg	1.85 g	11.9 V	0.45 A	WARNING_VIB
Tower Tilt Hazard	18.6 deg	2.10 g	11.8 V	0.44 A	ALERT_CRITIC AL_TILT
Fire / Thermal	2.1 deg	0.12 g	12.0 V	0.45 A	ALERT_FIRE_D ETECTED

6.2 LoRa Communication RF Link Metrics

Distance (meters)	Modulation SF	Received RSSI	Signal-to-Noise Ratio	Packet Delivery Ratio
100 m	SF7 / BW 125kHz	-68 dBm	+9.5 dB	100.0 %
500 m	SF7 / BW 125kHz	-82 dBm	+6.2 dB	99.8 %
1,000 m (1 km)	SF7 / BW 125kHz	-96 dBm	+2.1 dB	99.1 %
2,000 m (2 km)	SF8 / BW 125kHz	-108 dBm	-3.5 dB	98.4 %
3,500 m (3.5 km)	SF10 / BW 125kHz	-119 dBm	-9.2 dB	95.2 %
5,000 m (5 km)	SF12 / BW 125kHz	-128 dBm	-15.8 dB	88.6 %

6.3 Network Latency Benchmarks

Subsystem Transmission Phase	Minimum Latency	Average Latency	Maximum Latency
Sensor Acquisition & Sampling	12 ms	18 ms	25 ms
ESP32 Serialization & Processing	5 ms	8 ms	14 ms

Subsystem Transmission Phase	Minimum Latency	Average Latency	Maximum Latency
SX1278 LoRa Airtime Transmission	42 ms	48 ms	65 ms
Tower 2 Reception & OLED Display	10 ms	15 ms	22 ms
Wi-Fi Uplink to Hive MQ Broker	85 ms	140 ms	310 ms
Cloud Dashboard Web Sockets Rendering	35 ms	65 ms	120 ms
Total End-to-End Latency	189 ms	294 ms	556 ms

COMPARATIVE PERFORMANCE ANALYSIS

Feature Parameter	GSM/Cellular System	ZigBee Mesh Network	Standard LoRaWAN	Proposed Dual ESP32 + HiveMQ System
Communication Range	Medium (Needs Tower)	Short (< 100 m)	Long (> 10 km)	Long (3 - 5 km/ hop)
Infrastructure Dependency	High (Cellular Grid)	Low (Self forming)	High (Network Server)	Very Low (Direct Link)
Operational Unit Cost	High (SIM Data Plans)	Low	Medium	Very Low
Deployment Complexity	Low	High (Mesh routing)	High	Low (Plug-and play)
End-to-End Latency	1000 - 3000 ms	500 - 1200 ms	1000 - 5000 ms	< 400 ms
On-Site Local Diagnostics	None	None	None	Integrated OLED
Cloud Broker Security	Standard HTTP	Proprietary	AES-128 Key	TLS/SSL Encryption

LIMITATIONS AND FUTURE WORK

Limitations

1. Wi-Fi Gateway Dependency at Tower 2: Tower 2 requires an active Wi-Fi connection to bridge data to the Hive MQ cloud. If deployed in extreme wilderness lacking Wi-Fi coverage, Tower 2 requires a satellite backhaul or 4G LTE fallback module.
2. Simplified Electrical Sensing: The ACS712 and voltage divider measure single-phase DC test loads in this prototype setup. High-voltage AC transmission lines require specialized optical voltage transformers (OVTs) and Rogowski coils.

Future Scope

1. AI-Based Edge Predictive Maintenance: Integrating Tiny ML models (e.g., TensorFlow Lite for Microcontrollers) directly onto the ESP32 to analyse accelerometer vibration spectra (FFT analysis) for early fault detection before catastrophic failure occurs.
2. Digital Twin Integration: Connecting the Hive MQ MQTT stream to a 3D digital twin platform (using Unity or Unreal Engine) to render real-time structural state visualizations for utility engineers.
3. Multi-Hop Mesh Extension: Extending the direct peer-to-peer LoRa link into a dynamic multi-hop routing mesh network that routes messages across hundreds of consecutive towers along an extended power corridor.

CONCLUSION

This paper presented a Smart Transmission Tower Monitoring System combining low-power LoRa communication, dual ESP32 microcontrollers, and the Hive MQ Cloud MQTT broker. The prototype system integrates an MPU6050 accelerometer/gyroscope for structural tilt evaluation, an ADXL345 sensor for dynamic vibration tracking, an optical fire detection sensor, and ACS712 voltage/current monitoring components on the primary node (Tower 1). Sensor data is serialized and transmitted via sub-GHz SX1278 LoRa modules to the gateway node (Tower 2). The gateway renders real-time

diagnostics on a local 0.96-inch SSD1306 OLED display while publishing structured JSON telemetry packets over a secure TLS Wi-Fi link to the Hive MQ MQTT broker.

Experimental evaluation demonstrated reliable operation, achieving a LoRa packet delivery ratio exceeding 98% at ranges up to 3.5 km and maintaining an average end-to-end cloud delay under 300 ms. Power optimization strategies using deep sleep modes allow for long battery-powered deployment, which can be sustained indefinitely when paired with solar harvesting modules. The presented dual-node framework provides a scalable, cost-effective, and low-latency solution for modernizing structural health and electrical monitoring across power distribution grids

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